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ADVANCED BRISTLE SEALS FOR GAS TURBINE ENGINES

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Cabe, Jerry L.

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Engineered Designs, Inc.
4733 Devitt Drive
Cincinnati, Ohio 45246

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A seven month proof-of-concept program was conducted for an advanced bristle seal, called a bush seal, for use in gas turbine engines. This program was performed as a Small Business Innovation Research (SBIR) Phase I project.

Bush seal specimen and a full ring bush seal were designed, evaluated, and manufactured for testing. An analytical study of the potential of the bush seal relative to a labyrinth seal was conducted. Static and dynamic testing of the bush seal was performed to determine the behavior of the bristles under pressurization and during contact with a rotating labyrinth tooth.

Stable behavior of the bristle elements was observed during static pressurization of a full ring bush seal. The dynamic testing of various configurations of bush seal against a rotating labyrinth tooth showed minimal wear of the bristles relative to a conventional labyrinth seal.

The development and application of the bush seal concept to gas turbine engines has the potential of improving the engine's performance while decreasing the degradation of the seal performance over time.

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PREFACE

This report describes the work performed by Engineered Designs, Inc., Cincinnati, Ohio, under Department of the Army Contract DAAJ02-92-C-0008. This is the final report and covers the period of May 1992 to November 1992.

This program was aimed at determining the feasibility of an advanced bristle seal concept for application to gas turbine engines. This proof-of-concept program was sponsored under the Department of the Army Small Business Innovation Research (SBIR) program by the U.S. Army Aviation and Troop Command (ATCOM)*, Aviation Applied Technology Directorate (AATD), Fort Eustis, Virginia. The Technical Contracting Officer's Representative was Mr. Philip LaFerriere of AATD. The Principal Investigator and Program Manager was Jerry Cabe of Engineered Designs, Inc.

* Program was initiated by Aviation Systems Command (AVSCOM) prior to organizational name change in October 1992.

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BUSH SEAL CONCEPT

In 1988, Engineered Designs, Inc. initiated the development of an innovative bristle seal concept for use in gas turbine engine applications. This early development effort was limited to conceptual design and manufacturing methods evaluations. In May 1992 a contract between AVSCOM and Engineered Designs, Inc. was initiated to develop an advanced bristle seal with operational capabilities to 1450°F and 1450 feet per second tip speed evolving from the previous work. This contract effort was conducted as a Phase I Small Business Innovation Research (SBIR) program.

The advanced bristle seal covered by this contract is called a "bush seal". Figure 1 compares the features of a conventional labyrinth seal with those of a bush seal. Because the bush seal does not have to be designed for the worst case of combined thermal, mechanical, and rotor movement effects, the initial radial gap can be smaller than that of the conventional labyrinth seal. The bush seal's radial gap will also not be permanently increased during rubs caused by transients or rotor excursions as in a conventional labyrinth seal with abradable surfaces. This is because the bristles of the bush seal are spread apart during a

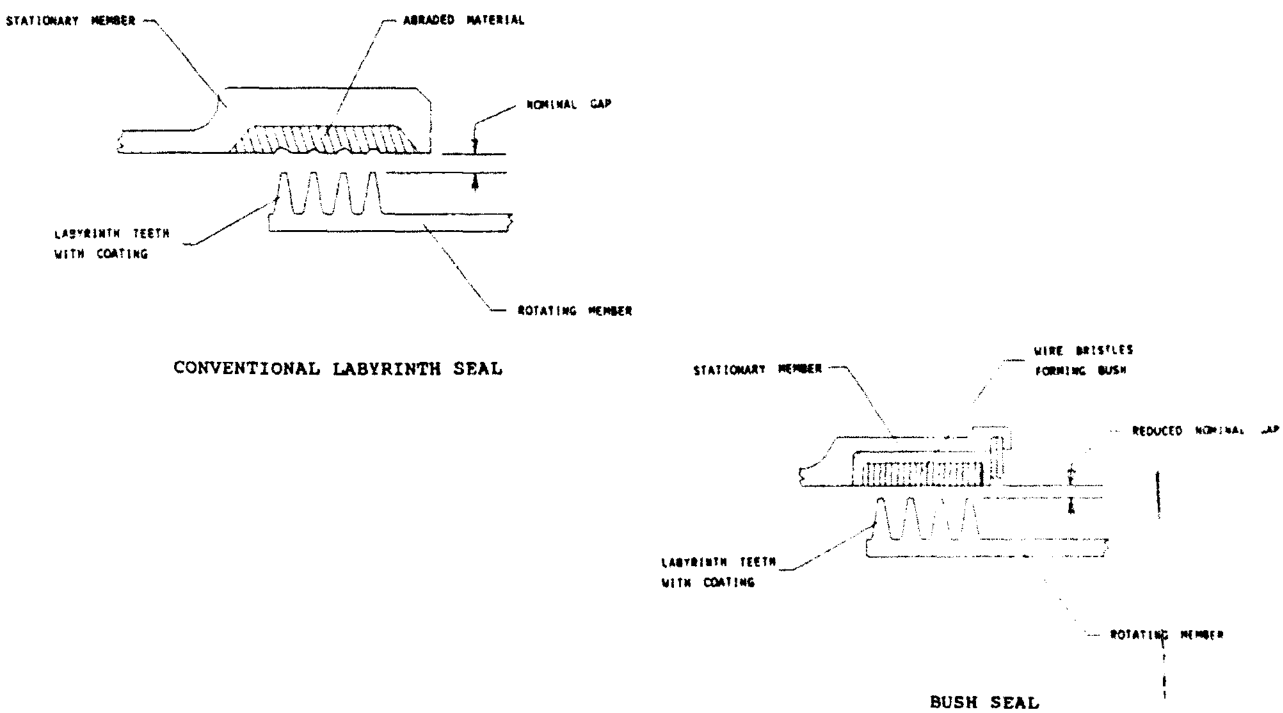

FIGURE 1. BUSH SEAL CONCEPT

rotor excursion by the rotating labyrinth teeth, but then return to a normal position after the excursion. This phenomena prevents major seal clearance changes, typical for the conventional labyrinth seal, which effect the performance of the seal.

The efficient operation of today's gas turbine engine relies on the performance of seals to control the amount of parasitic gas flow between rotating and stationary components of the engine. Labyrinth seals are routinely used throughout the primary flowpath and the secondary air system of gas turbine engines to limit this flow. Recently, bristle seals, called brush seals, have been used in selected applications because they promise improved engine performance through reduced leakage. However, these bristle seals are currently limited in temperature and surface speed capabilities and fall short of the desired operational goals. The bush seal concept utilizes bristle seal techniques to improve performance in the aggressive gas turbine engine environment, while allowing rotor to stator contacts without permanently damaging the seal. By preventing permanent changes caused by rubbing during rotor excursions, the seal's contributing portion to the cycle efficiency of the engine will be maintained, even in extreme environments.

PHASE I PROGRAM OBJECTIVES

The overall objective of Phase I of this SBIR project was to demonstrate the feasibility of the bush seal concept for future applications to gas turbine engines. Because the technical effort of a SBIR Phase I contract is limited to a six month effort, short duration proof of concept tasks were conducted. These included the definition and evaluation of manufacturing methods which would permit bush seal samples to be made and tested, conducting an analytical study to predict the relative performance of the bush seal to a conventional labyrinth seal, the dynamic testing of bush seal samples against a rotating labyrinth seal tooth, and the static testing of a full scale bush seal to determine the behavior of the bristles to pressurized flow.

WORK CARRIED OUT DURING PHASE I

A Research and Development program was proposed for Phase I which would allow the bush seal concept to be demonstrated. The proposed work scope and schedule which were submitted with the Phase I Proposal in 1991, were modified during the contract negotiations to incorporate dynamic testing of bush seal specimen and a Phase I briefing at Ft. Eustis. Figure 2 shows the planned tasks and schedule which were agreed upon for the Phase I contract. Task 1 covered the design and fabrication of the static and dynamic bush seal test articles. The procurement of the test assembly hardware was Task 2. The potential performance improvement of the bush seal was studied as Task 3. Tasks 4 and 5 performed the static and dynamic testing of the bush seal test articles. The periodic reporting, final reporting, and briefing were conducted as Tasks 6 and 7 of the program.

All Tasks were performed at Engineered Designs' offices in Cincinnati, Ohio. Minor changes to the planned schedule were incorporated because additional static and dynamic testing were performed at the end of Phase I which required the Final Report to be submitted at the end of November. This was determined to be acceptable since the contract actually specified a six month technical effort with one month additional for reporting.

The following sections describe what was performed for each of the agreed upon tasks.

TASK 1 - BUSH SEAL TEST ARTICLE DESIGN AND MANUFACTURE

The evaluation of various manufacturing methods to produce bush seal test articles had been ongoing at Engineered Designs and was continued as part of Phase I. Evaluations had been conducted prior to the award of this contract to determine the best possible method for generating low temperature specimen for testing, as well as the best candidate method for actual hot engine environment testing.

For the room temperature testing of Phase I, both dynamic and static testing, it was decided to utilize a high temperature capability bristle material, Haynes 25, which is a cobalt based alloy. This material was chosen because it is readily available in the small diameters required for bristle seals, and would allow easy transition to a high temperature application. Diametral size of the individual bristles used in Phase I was chosen to be .0028 inch for the same reasons.

The method of fabricating the bristles into a bush seal was accomplished by fixturing and welding the individual bristles into bundles which contain approximately 850 individual bristle wires.

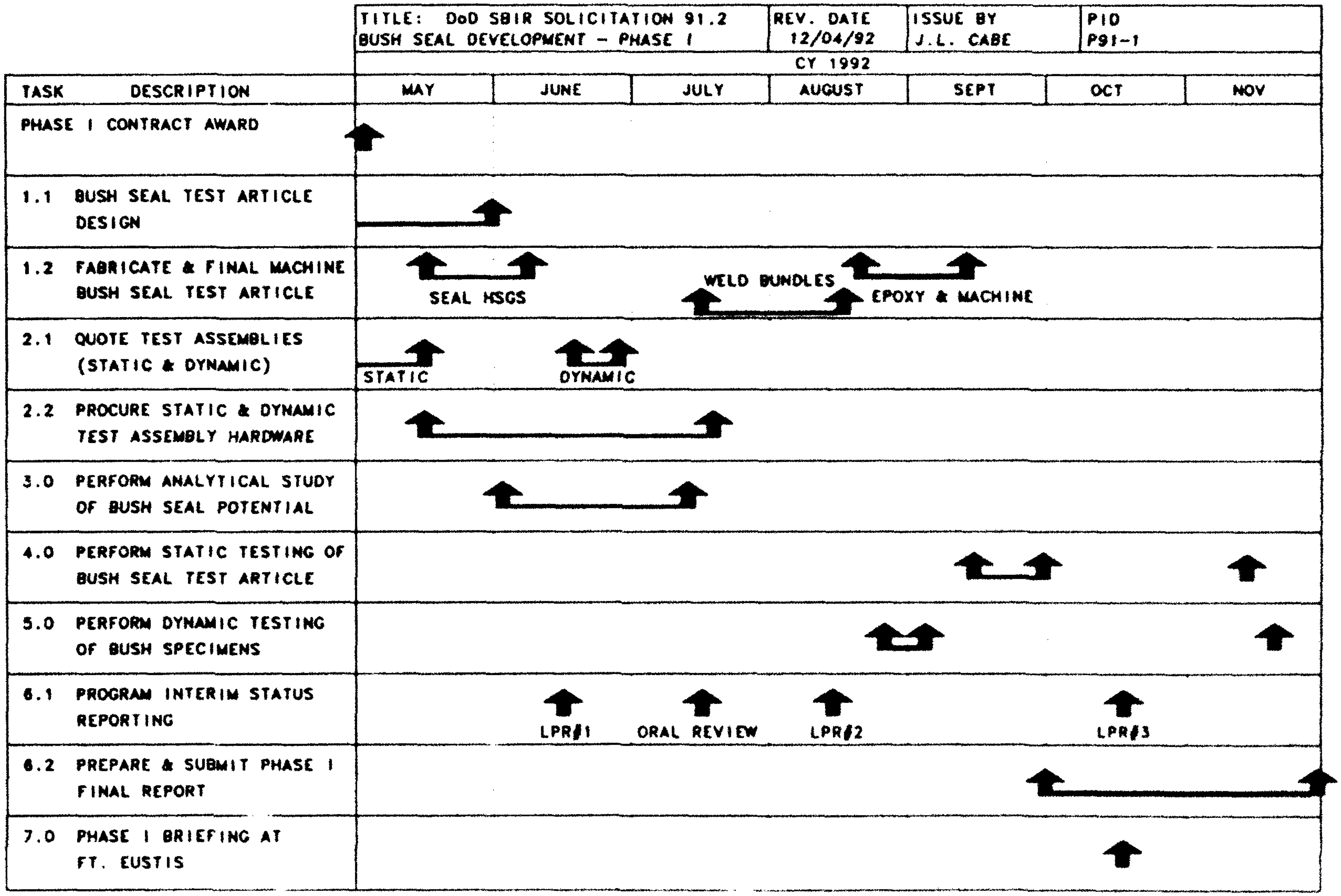

FIGURE 2. BUSH SEAL PHASE I SCHEDULE

Figure 3 shows one of the bristle bundles as welded. These bundles were then fixtured and attached to a housing in various arrangements. The attachment method for this portion of the development was chosen to be an epoxy. A moderate temperature capability (375^{o}F) silver based epoxy was used. The silver allowed the adhesive to be electrically conductive which was required for a subsequent machining operation, and the temperature capability allowed the test article to be tested with warm air which had been heated due to compression.

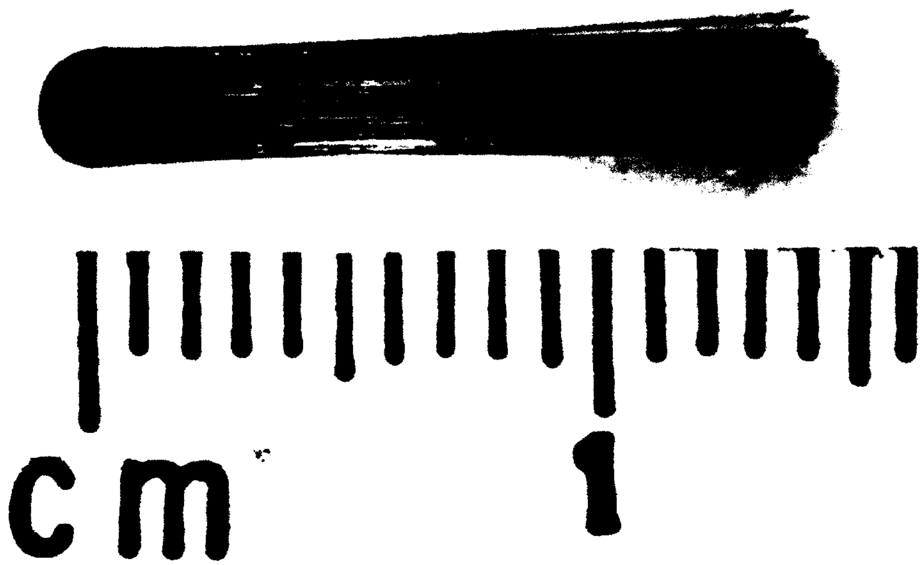

FIGURE 3. BRISTLE BUNDLE AS WELDED

Two types of test articles were designed. A small subscale specimen was designed for dynamic testing with a rotating labyrinth tooth. Three configurations of the subscale specimen were manufactured and tested in which the angle of the bristles was varied relative to a normal radial position. Based on the results of the dynamic testing, one angle was chosen for the design of a full ring bush seal test article to be used for static testing.

During the manufacturing of the test articles, various bundle fixturing methods were investigated for use during the curing cycle of the epoxy. Lessons learned here may also be applicable to a high temperature bundle attachment method if brazing is utilized.

After the bristle bundles were arranged and epoxied to the housings, the free tips of the bristles were machined to a finished dimension. For the subscale dynamic specimen, the tips were machined to a plane parallel to the base of the housing and perpendicular to a normal radial position. The full ring bush seal was machined to a diameter which was slightly larger than the outside diameter of the labyrinth teeth of the static test head. For all test articles, the machining was performed by wire Electrical Discharge Machining (EDM). This method allows close tolerance machining without deflecting the small diameter bristles. By using the silver based epoxy, the EDM'ing could be accomplished by having one electrode clamped to the specimen housing instead of to the bristles which were being machined.

TASK 2 - PROCUREMENT OF TEST HEAD HARDWARE

Test head hardware required for the static and dynamic testing was procured from outside vendors using Engineered Designs' Procurement System. The test head for conducting the static test had been designed and detailed prior to initiation of the contract. The main test head hardware is identified in Assembly P893A001 (Appendix A). Quotations for the manufacture of this hardware had been solicited previously for inclusion in the Phase I proposal. Because the quotations had expired before award of the contract, the hardware was requoted from three potential sources. The low quote was selected, and manufacture of the hardware was awarded to the Trotwood Corporation of Trotwood, Ohio.

Since the dynamic testing had been incorporated during the contract negotiations, the test setup, as well as the detail hardware required for this testing, was designed, detailed, and quoted. Required hardware included the specimen holders, and a rotating labyrinth tooth. Other adaptive hardware and fixturing already existed. The Trotwood Corporation manufactured the specimen holders and Promac, Inc. of Enon, Ohio manufactured the rotating seal.

Instrumentation required for the testing and other expendable hardware was also procured through Engineered Designs' Procurement System.

TASK 3 - ANALYTICAL STUDY OF BUSH SEAL PERFORMANCE

Because the concept of the bush seal is seen as a compromise between the conventional labyrinth seal and the brush seal which is being developed by many engine and seal manufacturers, a parametric study of the performance of a bush seal was conducted. A simple equation by Vermes (Appendix B) was used for this evaluation. Equation parameters of seal diameter, pressure ratio, discharge coefficient, air temperature, and radial clearance were varied.

Seal performance enhancements were determined for the bush seal versus a conventional labyrinth seal for typical engine environments. The performance differed because of the assumed differences in how the clearance changed after a seal rub. This is because it is believed that the bush seal can incur rubs with minimal dimensional change while the conventional labyrinth seal's clearance is opened up to the amount of the rotor excursion, and remains open to this degree under all operating conditions thereafter.

TASK 4 - PERFORM STATIC TESTING OF BUSH SEAL TEST ARTICLE

Static testing of the full ring bush seal test article was conducted to determine the performance characteristics of the seal as well as to determine how the bristles reacted during pressurization. The manufactured test article was installed into the static test head assembly. The static test head assembly was attached to the pressurized air supply as shown in the schematic of Figure 4. This set-up consisted of a 375 CFM compressor, filter, regulator, flow meter, and instrumentation.

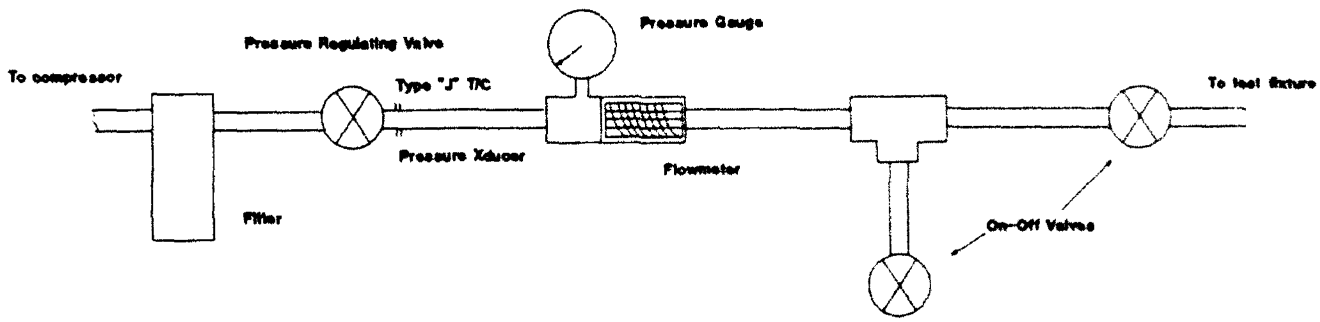

FIGURE 4. STATIC TEST AIR SYSTEM SCHEMATIC

Testing was conducted by supplying pressurized air to the upstream side of the bush seal, and measuring the air flow through the system caused by the pressure differential across the bush seal.

Because of a damaged area of the bush seal test article in which some of the bristle bundles became disbonded, the original test plan sequence identified in Figure 5 was not strictly followed. Periodic removal of the test head covers to visually inspect the bristles during each test sequence was not performed. The decision not to perform these inspections was based on the possibility of additional damage to the test article in the area of the loose bundles due to assembly and disassembly. Because the measured flow kept repeating each time the 10 psid point was set, it was felt that no significant change to the seal was occurring.

DATA POINT	DIFFERENTIAL PRESSURE
01	10 psid
Visual inspection of test article with covers removed.	
02	10 psid
03	15 psid
04	10 psid
05	20 psid
06	10 psid
07	30 psid
08	10 psid
09	40 psid
10	10 psid
Visual inspection of test article with covers removed.	
11	50 psid
12	10 psid
13	60 psid
14	10 psid
Visual inspection of test article with covers removed.	
15	70 psid
16	10 psid
17	80 psid
18	10 psid

Note: 1) Test article to be weighed before and after testing.
2) After stabilization at each data point, visual inspection of test article to be performed through polycarbonate cover plate

FIGURE 5. TEST PLAN FOR STATIC TEST OF BUSH SEAL

The test sequence consisted of a series of increasing pressure differential increments, each of which was followed by a return to a 10 psid check point. Because of pressure drops in the system, and seal flows which were larger than expected, the maximum differential pressure test points could not be conducted with this test setup.

After completion of the first test sequence, the test head forward cover and labyrinth teeth were removed for inspection of the bush seal test article. A second test sequence was conducted in which the metal front cover was replaced with one made of a clear poly-carbonate material. This setup allowed the behavior of the bristles to be visually determined during pressurization.

After the results of the static testing were studied, it was determined that higher flows were experienced than were predicted. Potential causes were determined to be: that the calibration and/or correction of the flowmeter was inaccurate; that the test article radial gap was different during pressurization than was measured statically; that there was air flow through the bristle bundles or some other unaccounted for leakage; or a combination of these possibilities. Additional static test sequences were conducted to determine the discrepancy in flow.

TASK 5 - DYNAMIC TESTING OF BUSH SEAL SPECIMEN

Dynamic testing of the subscale bush seal specimen was added to the Phase I effort during the contract negotiations. The objective of this testing was to determine the interaction of the bush seal and a rotating labyrinth tooth under low speed conditions. For this testing, the bush seal test specimen were mounted such that a rotating tooth could be displaced into the bush seal bristles to simulate a rotor excursion.

A ten inch diameter labyrinth tooth was directly mounted onto a motorized drive head which has the capability of three axis motion. This setup allowed the rotating seal tooth to be moved in directions which simulated a radial or a radial plus axial rotor excursion. The test head motor was rated at 3450 RPM which allowed a labyrinth tooth tip speed of approximately 150 feet per second.

As previously indicated, three configurations of subscale specimen were manufactured with different bristle lay angles (the angle of the bristles relative to a normal radial orientation). Two specimen were made with a zero degree lay angle, one with a 30 degree lay angle, and one with a 45 degree lay angle.

One each of the three different lay angle configurations was dynamically tested by mounting the specimen perpendicular to the plane of rotation of the labyrinth tooth. Dynamic testing was accomplished by moving the rotating labyrinth tooth into the

bristles to depths of .005, .010, and .015 inch simulating various radial rotor excursions. Each specimen also had the labyrinth tooth moved into the bristle bundle to a depth of .010 inch and then traversed in a manner which simulated a combined radial/axial rotor excursion.

Extreme radial excursion testing was also conducted on the second zero lay angle specimen. In this test, the rotating labyrinth seal was engaged into the bristles to varying depths up to .050 inch.

After the briefing at Ft. Eustis, additional dynamic testing was conducted on another 45 degree lay angle specimen. For this testing, the rotating tooth was engaged into the bush seal for extended periods of time. Incursions into the bristles to a depth of 0.010 were conducted for periods of time of approximately 5, 30, and 60 seconds. Incursion depths of 0.015 were also conducted for approximately 30 and 60 seconds.

TASKS 6 & 7 - PERIODIC REPORTING, BRIEFING, AND FINAL REPORT

During the period of performance of this contract, Letter Progress Reports were submitted every second month per Contract Data Requirements List (CDRL) Item A001. These Letter Progress Reports documented the activities, status, and progress during the reporting period as well as the plans for the next reporting period. A final briefing on Phase I was conducted at Ft. Eustis, Virginia on October 19, 1992. Submission of this report completes the reporting and documentation of all Phase I activities, including the submission of a Final Report per CDRL Item A002.

RESULTS OF PHASE I

The various tasks identified for Phase I were worked over the seven months of the program. All objectives of the program were accomplished. Specific results for each of the Phase I program tasks are as follows.

TASK 1 - BUSH SEAL TEST ARTICLE DESIGN AND MANUFACTURE

Two types of bush seal test articles were designed and manufactured for testing during the Phase I effort. Subscale specimen with bristle surfaces of approximately 0.6 inch by 0.8 inch and a full ring bush seal with a 5.1 inch bore were manufactured.

Subscale specimen with various bristle lay angles, P/N P893M050, were designed for testing against a rotating labyrinth tooth. These specimen were manufactured by attaching the welded bristle bundles into a housing with a silver based epoxy. The first specimen, intended to be a zero lay angle specimen, tended to have gaps between the bundles. This resulted from improper fixturing of the bristle bundles during the curing of the epoxy. The second, third, and forth specimen (a 30 degree, 45 degree, and second zero degree lay angle) were manufactured in the same manner with fixturing added to group the bundles during the epoxy cure cycle.

After the epoxy had been cured on the specimen, wire EDM was used to machine the free bristle ends to form a flat surface. As mentioned, the first zero lay angle specimen had many voids in between bristle bundles due to inadequate fixturing, however, the second zero lay angle specimen had good grouping of the bristle bundles. The 30 and 45 degree lay angle specimen had only minor voids between the bristle bundles, but surface voids were created by bundles which were too short. Nonetheless, all four specimen had areas which were acceptable for testing. Figure 6 shows one of the 45 degree lay angle bush seal specimen which was tested.

The full ring bush seal test article, P/N P893G008, was designed to be installed and tested in the static test rig. The bristle bundles were epoxied into the bore of the seal housing with the bristles angled at a 45 degree lay angle. This was determined to be the preferred angle for bristle flexibility based on the dynamic testing which had already been conducted. Silver based epoxy was also used for the full ring bush seal test article because the test article was only intended to be tested at relatively low air temperatures.

The bore of the bush seal test article was machined relative to the rabbet diameter on the outside diameter of the seal housing using wire EDM. The bore was machined to a diameter of 5.1064 inch,

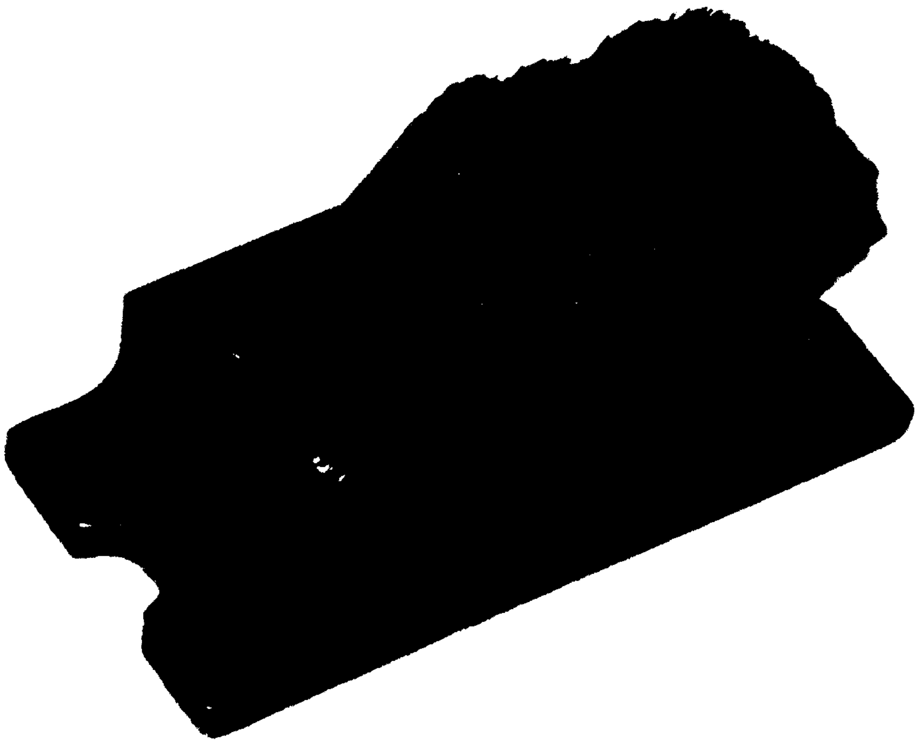

FIGURE 6. BUSH SEAL SUBSCALE SPECIMEN

which when combined with the outside diameter of the labyrinth toothed seal, would give a radial gap of .0032 inch. Figure 7 shows the bush seal test article after wire EDM'ing. Figure 8 is a close-up of the bush seal surface after the wire machining.

After careful inspection of the machined bush seal test article, it was found that some of the bristle bundles had become loose. Inspection of the loose bristle bundles indicated improper bonding, probably a result of insufficient epoxy. Minimal epoxy was being used for the full ring test article after it was found that too much epoxy was used on some of the subscale specimen, which resulted in epoxy wicking between the bristle bundles. Control of the amount of epoxy was difficult because it was being manually applied using a syringe.

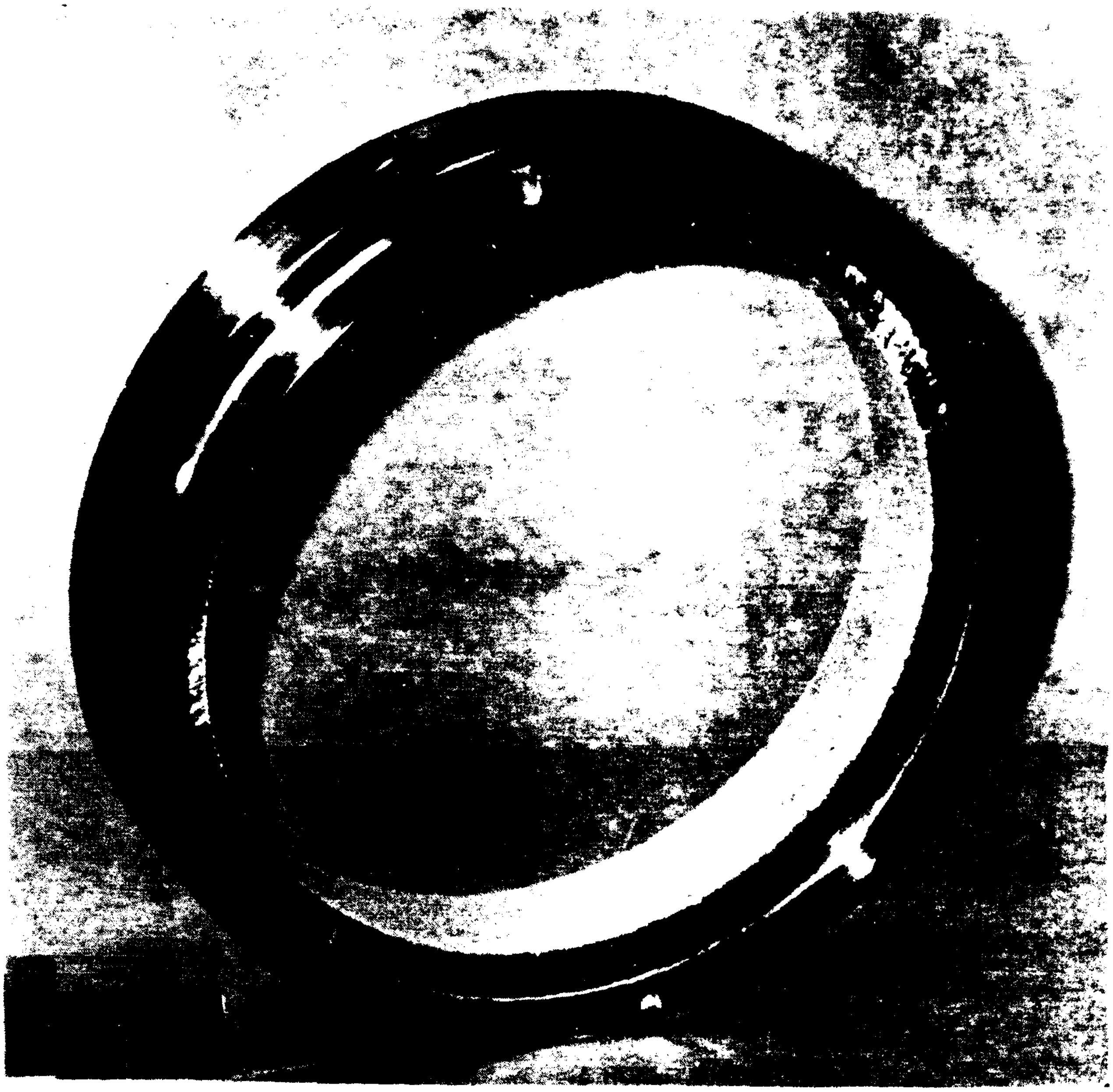

FIGURE 7. FULL RING BUSH SEAL TEST ARTICLE

The loose bristle bundles were replaced and re-epoxied. Approximately 28 of the 1860 bristle bundles in the test article were replaced. The bundle replacement required the bore of the bush seal test article to be remachined which resulted in a 5.110 inch bore, giving a 0.005 inch radial clearance with the test rig labyrinth teeth.

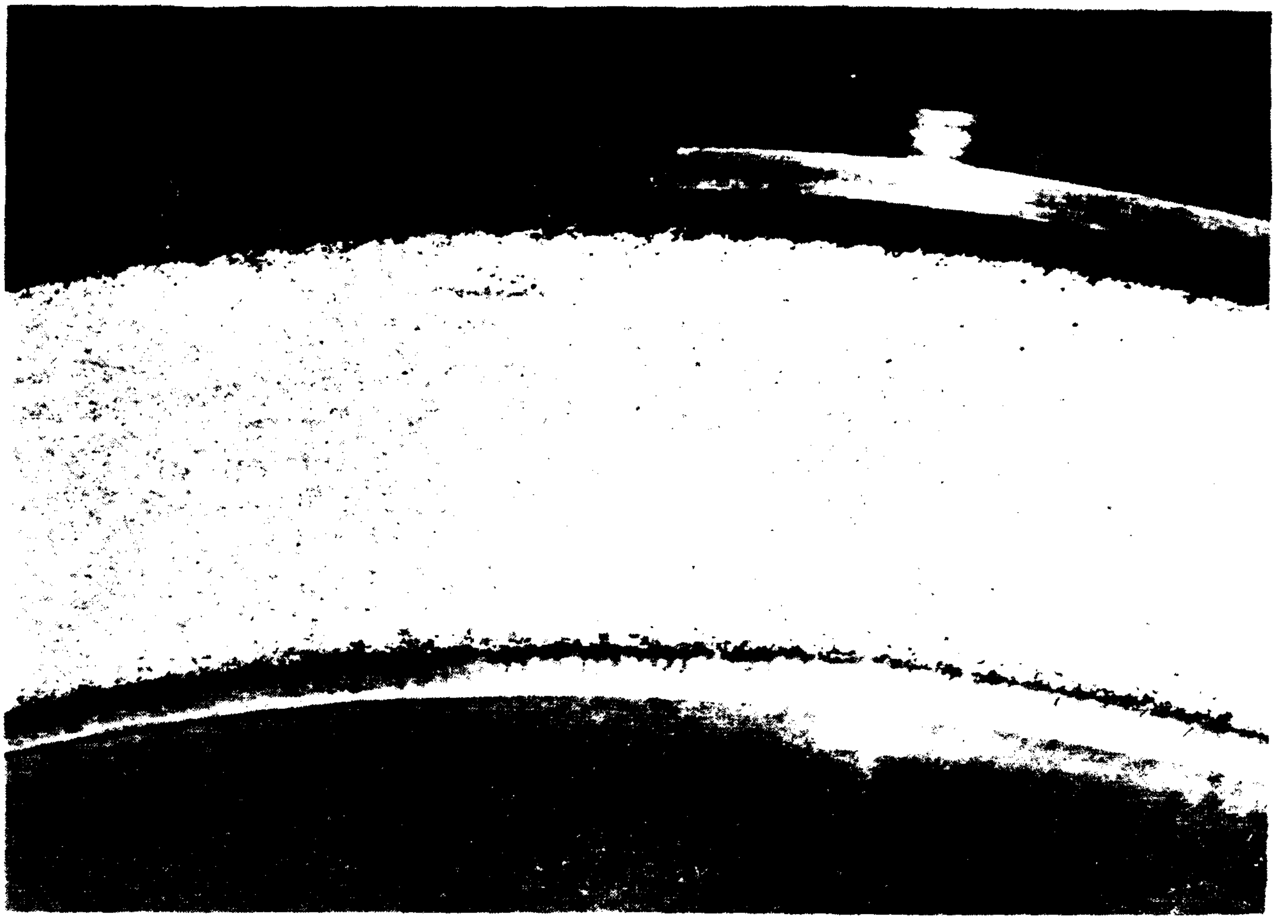

FIGURE 8. BUSH SEAL TEST ARTICLE SURFACE AFTER MACHINING

TASK 2 - PROCUREMENT OF TEST HEAD HARDWARE

All hardware for the Phase I effort was procured through Engineered Design's Procurement System. This included all material for the bush seal test articles, all hardware for the dynamic and static test rigs, as well as instrumentation and other expendables. All outside vendor manufactured hardware was visually inspected upon receipt. Minor, non-functional discrepancies were found and noted or corrected.

During assembly of the static test rig with the full ring bush seal test article, a dimensional stack-up problem was identified which resulted in the bush seal test article and the four tooth labyrinth seal not aligning axially in the rig. Dimensional inspection of all the hardware revealed one axial dimension on the seal support (Item 04 of P893A001) had not been machined per print which resulted in the misalignment. This problem was resolved during the static testing by using the back up ring (Item 25 of P893A001) as a spacer between the seal support and the main housing to axially align the components, as shown in Figure 9. This was an acceptable solution for the static testing, however, it did require careful

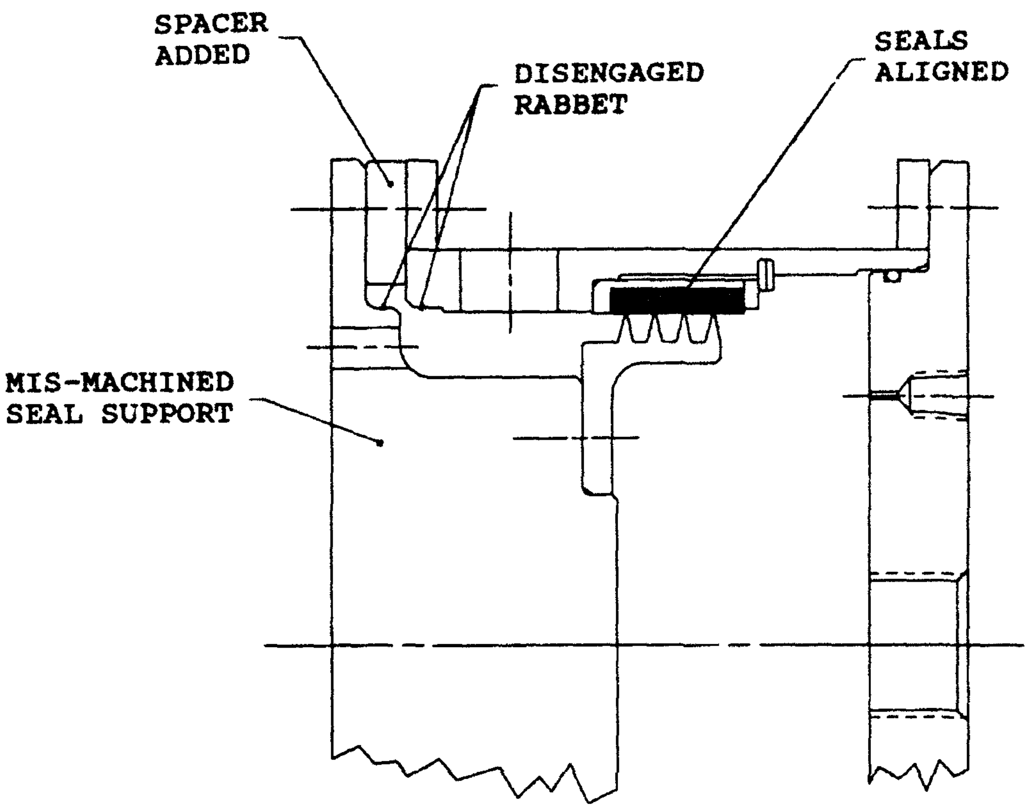

FIGURE 9. STATIC TEST HEAD AS ASSEMBLED WITH SPACER

alignment of the seal support to center up the four tooth labyrinth seal because the seal support no longer engaged the rabbet into the main housing. No other hardware discrepancies were identified.

TASK 3 - ANALYTICAL STUDY OF BUSH SEAL PERFORMANCE

Parametric studies were conducted using the Vermes orifice equation to determine the characteristics of labyrinth seals with a radial gap. Analysis was conducted in which the seal diameter, radial gap, pressure ratio, discharge coefficient, and air temperature were varied to cover typical gas turbine engine applications. Plots of the significant data were generated and used to determine labyrinth seal sensitivity characteristics. Copies of the data and plots were furnished to the Technical Contracting Officer in July.

These plots and characteristics are applicable to both conventional labyrinth and bush seals. The difference between the two is that the bush seal is believed to be capable of being operated with

smaller radial gaps than the conventional labyrinth seal. Because the bush seal does not have to be designed for the worst case of combined thermal, mechanical, and rotor movement effects, the initial radial gap can be smaller than that of the conventional labyrinth seal. The bush seal's radial gap will also not permanently increase during transients or rotor excursions as in a conventional labyrinth seal with abradable surfaces.

Studies of generic seals to determine the performance enhancement due to an assumed 50% reduction in operating clearance resulted in reductions in flow of 43 to 65 percent. The variability in reduction comes from changes in discharge coefficients because of radial gap changes.

A specific application study was conducted for three seal locations on the T700 turboshaft engine. These three seal locations are the compressor discharge pressure (CDP), the inner balance piston (IBP), and the outer balance piston (OBP). Intermediate rated power conditions were used for this study. For the bill of material condition, nominal seal clearances were used for each location. No field experience data was available, so it was assumed that the cold nominal clearances exceed all rotor excursions, i.e. no rotor rubs on the seals.

For the bush seal conditions, assumptions of similar tolerances for the rotating labyrinth teeth and a .001 inch diametral tolerance on the bore of the bush seal were made. A minimum radial clearance of .002 inch was assumed for assembly. From the results of the dynamic specimen testing, a .0025 inch radial wear was assumed. This results in a maximum .006 inch radial clearance for the bush seal at all three seal locations.

Again using the Vermes orifice equation, the seal leakages for the conventional labyrinth seal without rotor rubs or degradation, and the bush seal with assumed wear were calculated. The results are summarized in Table 1.

TABLE 1. PARASITIC AIR LEAKAGE AT T700 SEAL LOCATIONS

SEAL LOCATION	BILL OF MATERIAL RADIAL GAP	BILL OF MATERIAL FLOW	BUSH SEAL RADIAL GAP	BUSH SEAL FLOW
COMP. DISCHARGE PRESSURE SEAL	.0115"	.147 PPS	.0060"	.064 PPS
INNER BALANCE PISTON SEAL	.0110"	.148 PPS	.0060"	.068 PPS
OUTER BALANCE PISTON SEAL	.0290"	.154 PPS	.0060"	.049 PPS

Based on this analysis and assumptions, the T700 engine could reduce the parasitic air leakage by 0.27 lbm/sec by incorporating bush seal technology in these three locations. This reduction in parasitic air leakage can be used to improve specific fuel consumption (SFC) or to provide additional cooling to the engine's hot section to reduce temperatures and increase life. Additional life improvements can be realized if the bush seal concept is found not to degrade over time as does the conventional labyrinth seal. By not degrading, better control of the balance piston cavity can be accomplished, which in turn can increase the life of the rotor thrust bearings.

TASK 4 - PERFORM STATIC TESTING OF BUSH SEAL TEST ARTICLE

The initial static Test Sequences A and B were conducted per the modified static test plan discussed earlier. Upon installation of the full ring bush seal test article into the static test head, another area of loose bristle bundles was identified. This area is shown in Figure 10. It is thought that this area became unbonded because of the interference fit between the test head and the test article. Because of the relative stiffnesses, most of the fit would go into deforming the test article housing, which could break the epoxy bond. It was decided to continue with the static test, but to eliminate the three disassembly/assembly cycles of the rig during the test sequence.

FIGURE 10. LOOSE BUNDLE AREA OF TEST ARTICLE BEFORE TESTING

After running Test Sequence A, the front cover and labyrinth tooth seal were removed for visual inspection of the bush seal test article. The loose bristle bundle area is again shown in Figure 11 after running the first test sequence. Many loose bristle bundles were evident within approximately a 30 degree arc which created an uneven seal surface. Movement of these bristle bundles could be easily accomplished with light finger pressure.

FIGURE 11. LOOSE BUNDLE AREA OF TEST ARTICLE AFTER TESTING

In Test Sequence B, the metal front cover of the static test rig was replaced with a poly-carbonate cover which allowed visual observation of the high pressure side of the bush seal test article. No movement of the bush seal bristles, either deflection or vibratory, was observed. Visualization of the exposed bristles on the low pressure side were also observed to have no motion.

The test article was weighed before the initial testing and after Test Sequence B. No change in mass was measured, which would have been an indication of bristle loss.

The recorded and corrected data from these test sequences are tabulated in Appendix D as Tables D-1 and D-2. The results of this testing are plotted in Figure 12 along with the predicted flows using the Vermes equation. As can be seen, the flows are significantly larger than those predicted by Vermes. This discrepancy led to additional investigative test sequences being run.

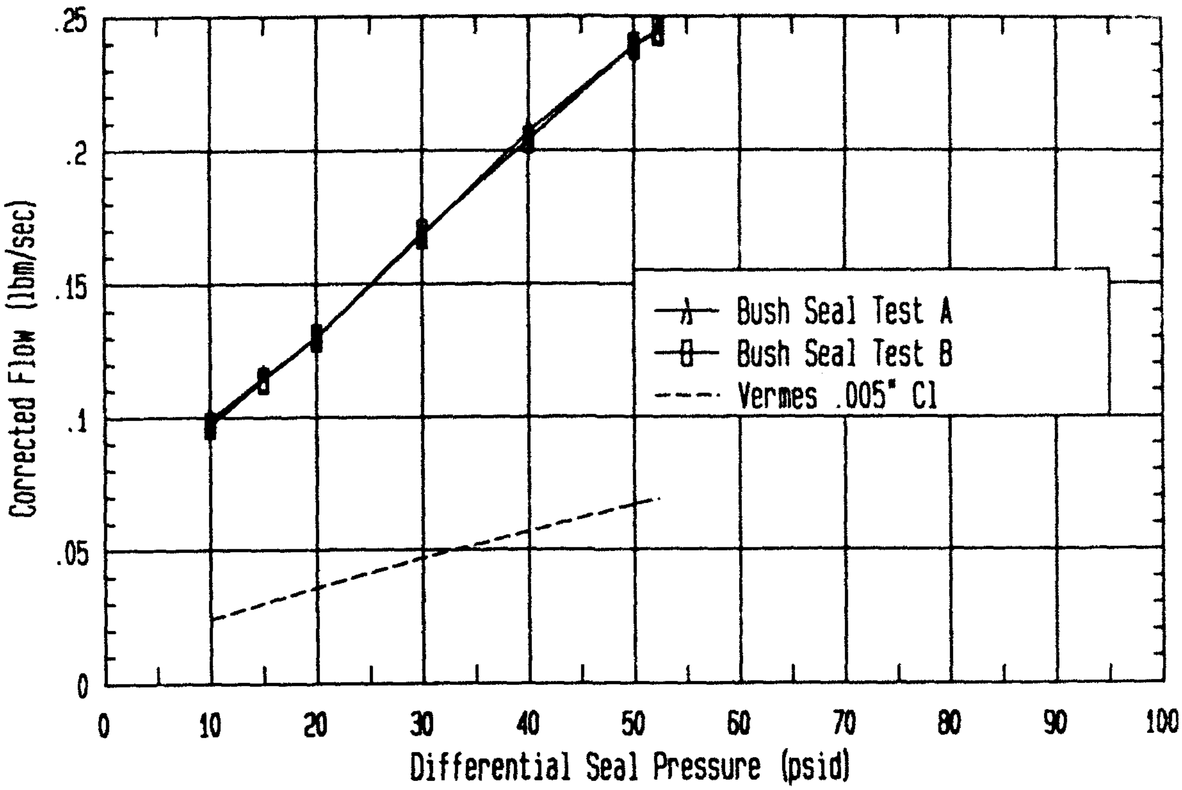

FIGURE 12. TEST SEQUENCES A & B VERSUS PREDICTED FLOW

Investigative Test Sequences C,D,& E were performed to determine if the positioning of the flow meter was incorrect. The vendor of the flowmeter indicated that some reading differences could be caused by the regulator being installed up stream of the flow meter. While no strong reason could be established because there were long straight sections of tube between the components, a simple test was conducted in which the regulator and flow meter were reversed. This testing was conducted with only a constricting orifice (a ‹ le nozzle) in place of the test head and test article. Data . these test sequences are tabulated in Appendix D, Tables D-3, ᴅ-4, and D-5. No significant differences were found as shown in Figure 13.

Investigative test sequence F used the original test setup with the static test head, but had the bush seal test article replaced with a solid metal ring. This ring had the same geometric shape as the bush seal test article, but the radial clearance between the labyrinth teeth and the ring bore was measured to be .003 inch. Table D-6 in Appendix D tabulates the data generated in this test sequence. The results of this testing, shown in Figure 14, confirmed that the flow meter calibration and pressure/temperature corrections were correct as well as that there were no unaccounted leakages in the system.

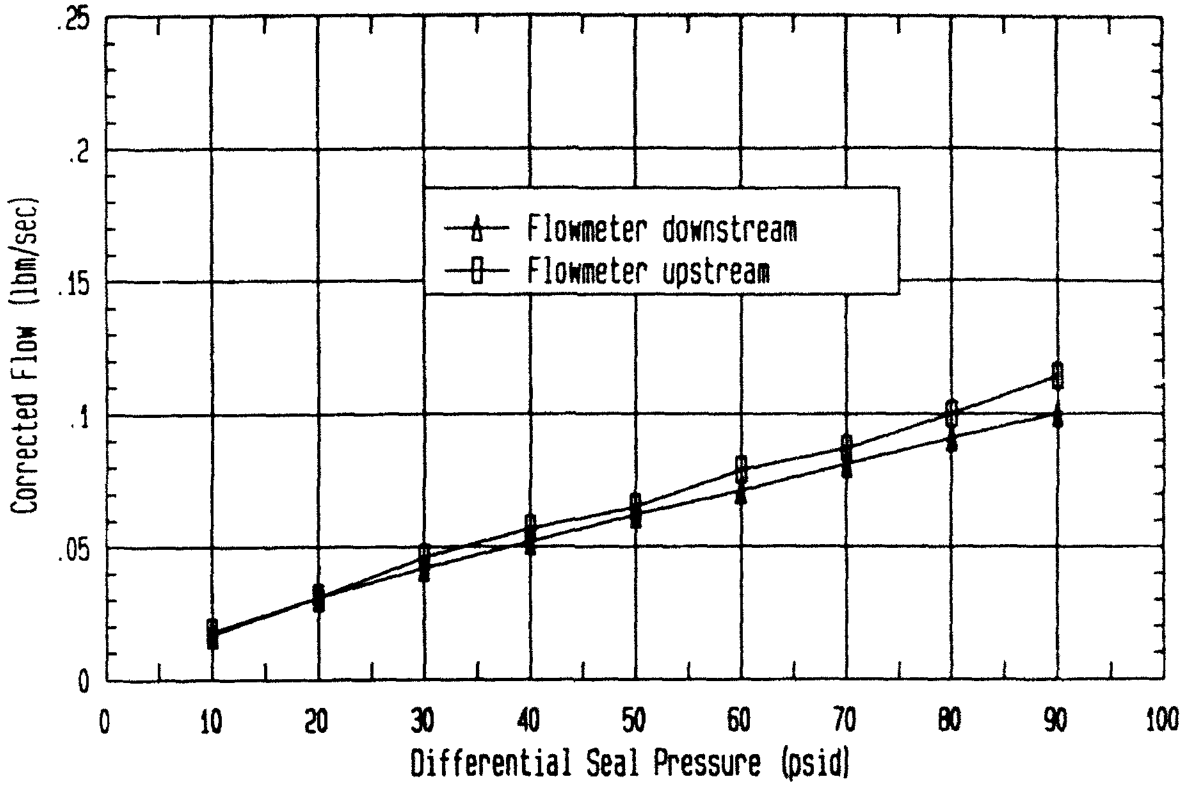

FIGURE 13. SIMPLE ORIFICES VERSUS PREDICTED FLOW

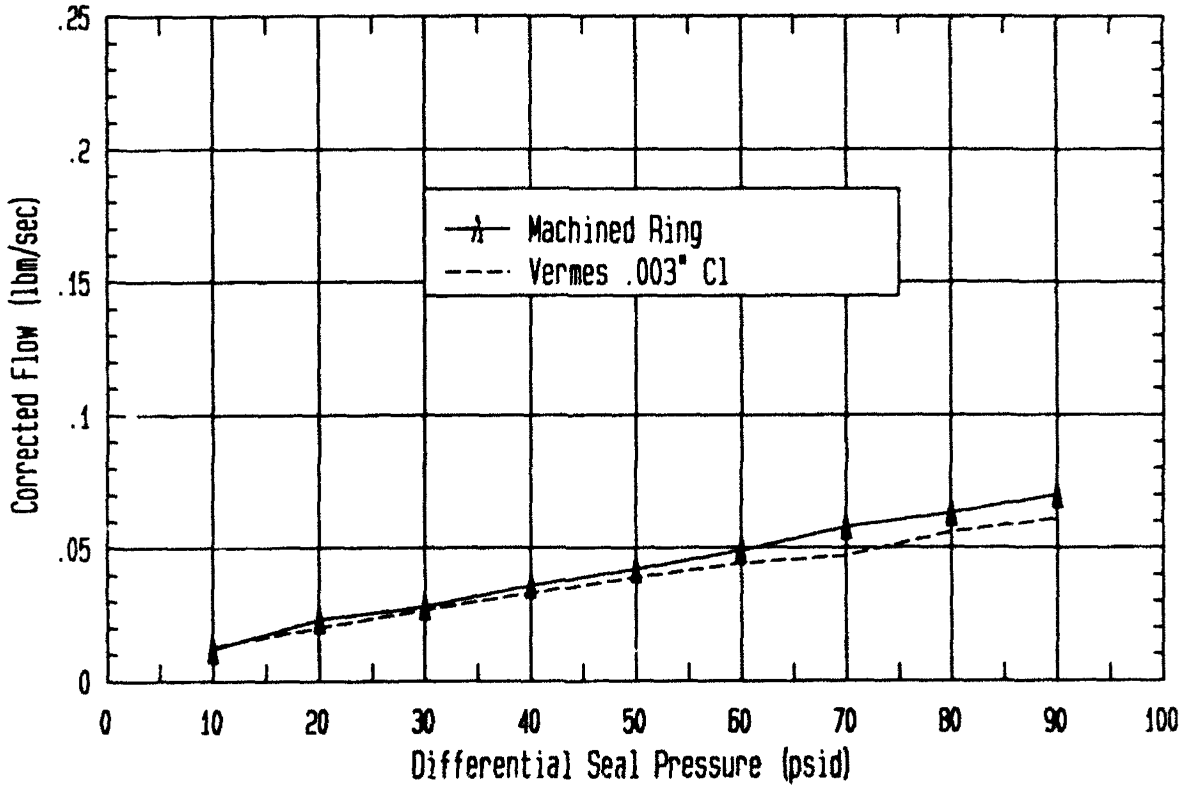

FIGURE 14. MACHINED RING VERSUS PREDICTED FLOW

Investigative test sequence G reinstalled the bush seal test article into the static test head and repeated the original test sequence. Investigative Test Sequence H involved inserting a .003 inch thick shim between the bush seal and the first labyrinth tooth as shown in Figure 15. This testing was done to determine the effect on the flow for a known change in the flow area. Tabulated data is contained in Appendix D, Tables D-7 and D-8. As expected, the results, plotted in Figure 16, repeated the results of the original test sequences.

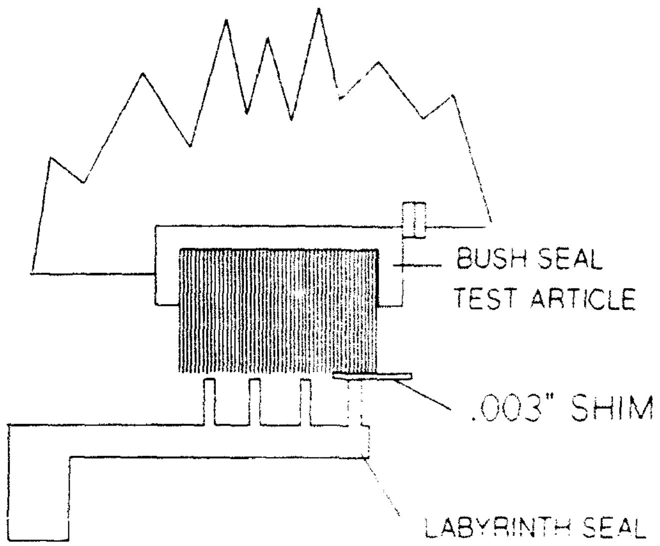

FIGURE 15. TEST SETUP WITH .003 INCH SHIM INSTALLED

Investigative test sequence I retained the .003 inch shim and added a positive seal between the shim stock and the housing using Room Temperature Vulcanizing (RTV) material to seal off the axial face of the bristles as shown in Figure 17. This forced all of the flow to go between the shim stock and the labyrinth teeth, at least for the first labyrinth tooth.

Investigative Test Sequence J removed the .003 inch shim stock while leaving the RTV seal on the face of the bristles. Almost all of the axial area of the bristles was closed off by the RTV seal as shown in Figure 18.

The collected data of test sequences H through J are tabulated in Appendix D, Tables D-8, D-9, and D-10. Plotted data is shown in Figure 19. This investigative testing tends to confirm that the bush seal test article was leaking through and/or around the bristle bundles. The exposed axial face of the bristle bundles gives the pressurized air access to the space between the bristle

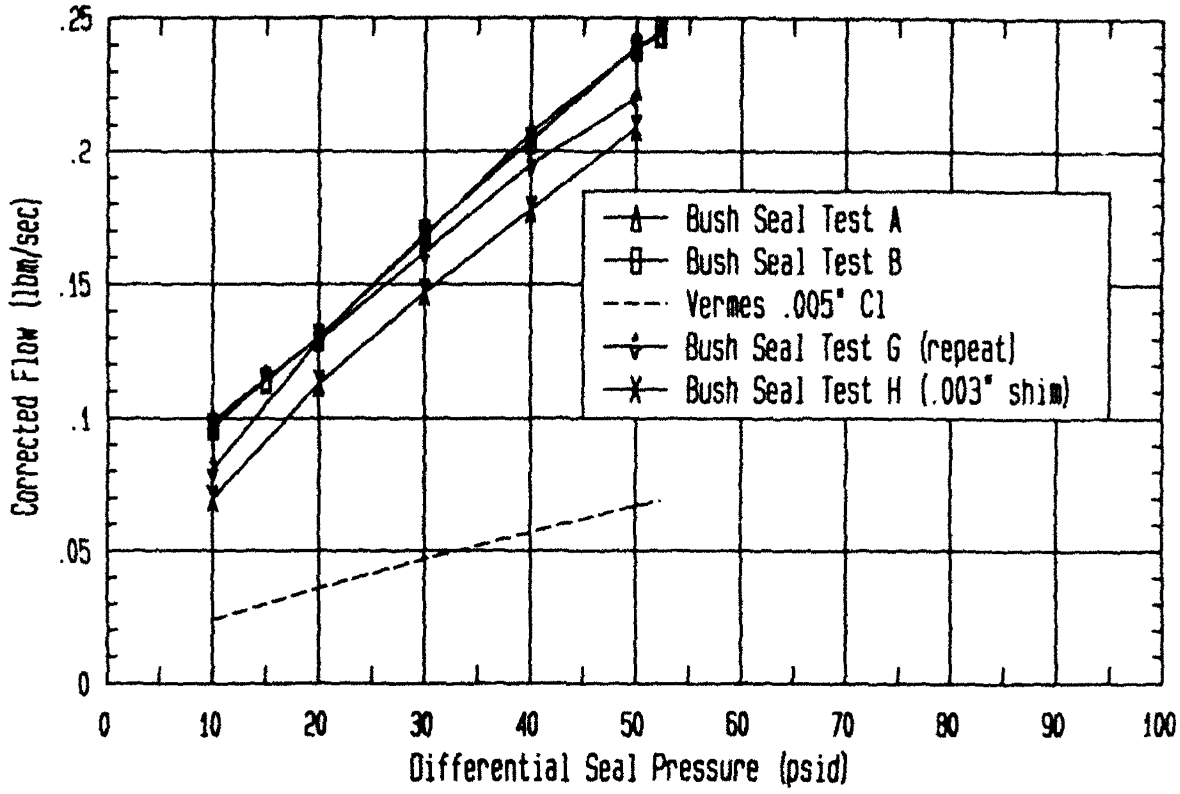

FIGURE 16. TEST SEQUENCES A, B, G, & H VERSES PREDICTED FLOW

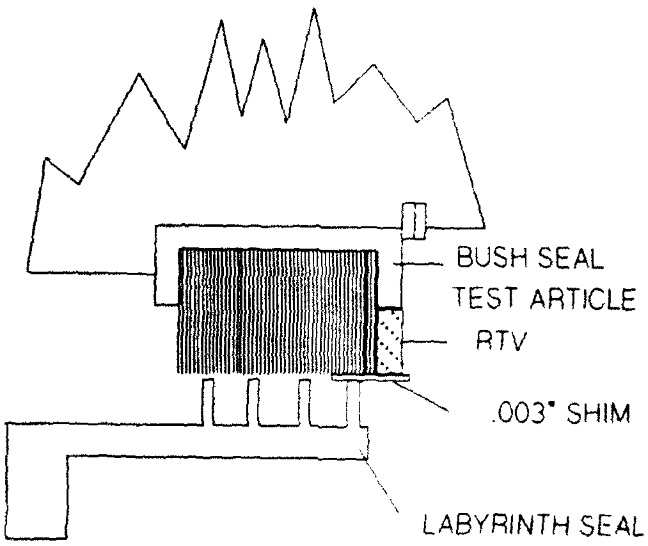

FIGURE 17. TEST SETUP WITH .003 INCH SHIM AND RTV SEAL

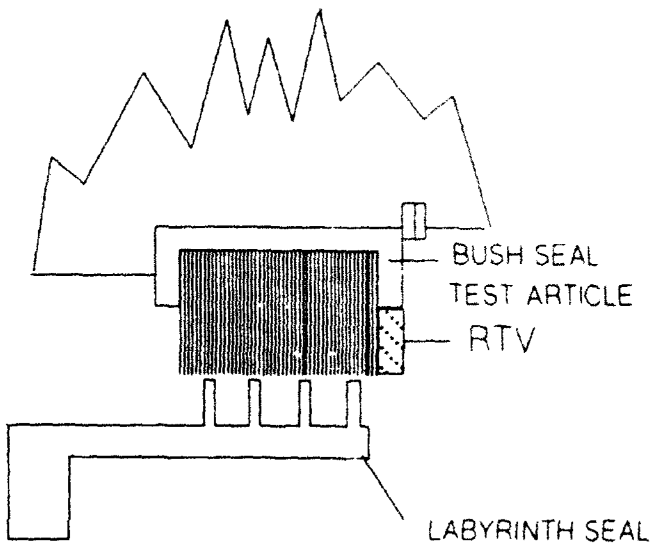

FIGURE 18. TEST SETUP WITH RTV SEAL

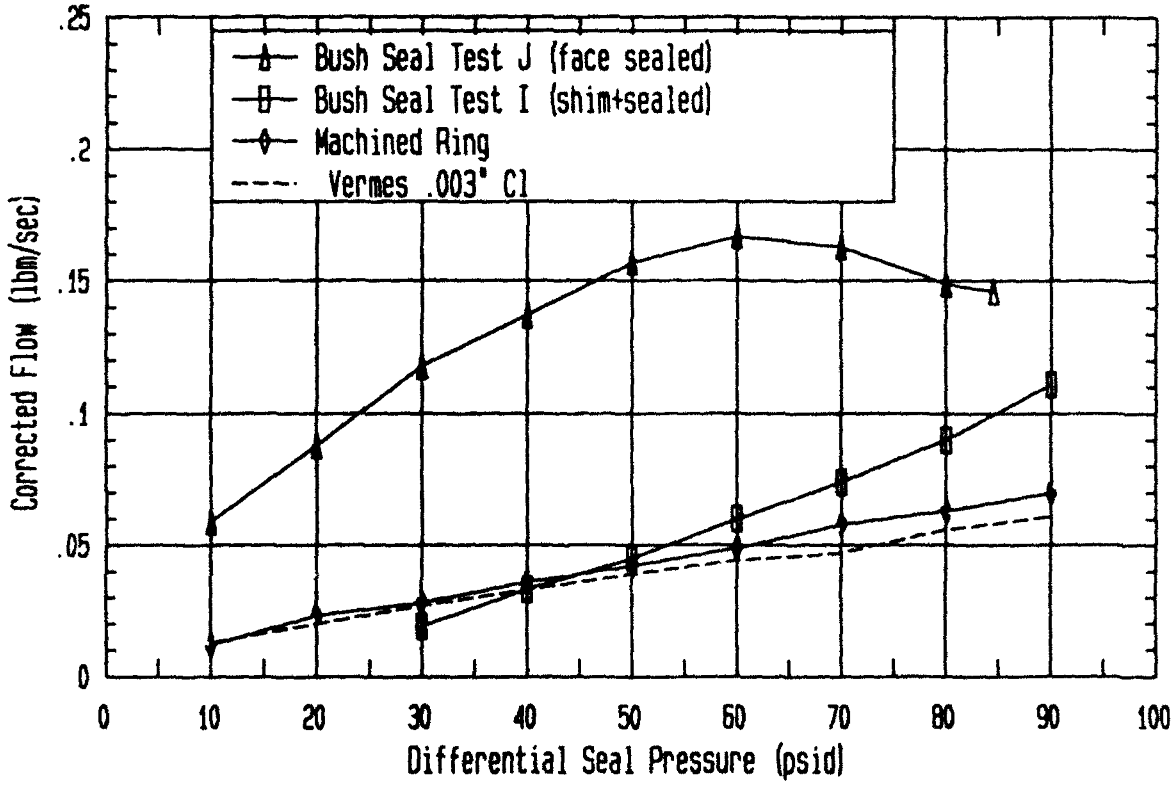

FIGURE 19. SHIMMED AND RTV SEALED TESTS VERSES PREDICTED FLOW

bundles. It was observed that during the testing with the shim, but without the RTV, that the bristle bundles in the loose bundle area did deflect in an axial direction. Visual observation of this same area during the testing with only the RTV showed the RTV dimpling in an axial direction, as well as deflecting radially inward at the higher pressure points. The deflection radially inward could explain the way the flow curve for this case changed with increasing pressure.

TASK 5 - DYNAMIC TESTING OF BUSH SEAL SPECIMEN

Dynamic testing of the bush seal was conducted by mounting each manufactured specimen in a test fixture. A non-rotating labyrinth seal tooth was brought into contact with the surface of the bush seal specimen, at which point a dial indicator which contacted the test head was zeroed out. The seal tooth was then positioned so that there was no contact with the specimen, the motor was energized, allowed to come up to full speed, and the now rotating labyrinth tooth was displaced into the specimen to a known depth as indicated by the instrumentation, and then backed out of the bush seal. The labyrinth tooth was subsequently repositioned to a new contact area and the test was repeated. The matrix of tests is shown in Table 2. Additional tests included extreme excursion testing and extended duration testing. These additional tests are discussed separately.

TABLE 2. BUSH SEAL DYNAMIC TEST MATRIX

TEST SPECIMEN	.005" RADIAL	.010" RADIAL	.015" RADIAL	.010" RADIAL/TRAVERSE
0° LAY ANGLE	X	X	X	X
30° LAY ANGLE	X	X	X	X
45° LAY ANGLE	X	X	X	X

Upon completion of the initial test matrix, the specimen was removed from the fixture and the "wear" track was measured using a trigger indicator with a .015 radius scribe. Visual inspection of the wear tracks with magnification showed that there was some spreading of the bristles. Also, some bristles showed a "smeared" appearance on the tips. It is unknown at this time if this appearance is wear or a transfer of chrome plating from the rotating labyrinth tooth. The dimensional inspection results of this test matrix are tabulated in Table 3.

TABLE 3. BUSH SEAL DYNAMIC TEST WEAR MEASUREMENT

TEST SPECIMEN	.005" RADIAL	.010" RADIAL	.015" RADIAL	.010" RADIAL/TRAVERSE
0° LAY ANGLE	.0015	.0020	.0015	.0025
30° LAY ANGLE	.0010	.0010	.0015	.0015
45° LAY ANGLE	.0010	.0010	.0015	.0010

NOTE: (1) TEST SPECIMEN MEASUREMENTS TAKEN AT MAX DEPTH.
(2) NO MEASURABLE WEAR ON LABYRINTH TOOTH.

Extreme excursion testing was conducted on one 0° lay angle specimen. This test consisted of several simulated rotor excursions in which the rotating labyrinth tooth was briefly displaced into the specimen to depths of 0.010, 0.015, 0.020, 0.030, 0.040, and 0.050 inch. The results of the extreme excursion testing were not quantified due to gaps between bristle bundles. This was the specimen which had bad fixturing resulting in gaps between the bundles. However, visual inspection of this specimen indicated no distress.

An extended duration test was added to the test program after the final briefing. The testing was conducted on one 45° lay angle specimen. The test sequence used for the extended duration test and the wear results are shown in Table 4.

TABLE 4. BUSH SEAL EXTENDED DURATION TEST

TEST TRACK	TEST CONDUCTED	MEASURED WEAR
1	.010" INCURSION FOR 10 SEC	.0020"
2	.010" INCURSION FOR 30 SEC	.0025"
3	.010" INCURSION FOR 60 SEC	.0025"
4	.015" INCURSION FOR 30 SEC	.0025"
5	.015" INCURSION FOR 60 SEC	.0020"

The conclusions that can be drawn from the dynamic testing are that the bush seal exhibits very favorable "wear" characteristics for low speed/low temperature environment. Compared to a conventional abradable seal, the wear characteristics are almost negligible.

As can be seen from the test data, the bush seal is relatively insensitive to depth of rub, and after some "initial wear" of .0010"-.0025" , wear does not appear to increase with time.

TASKS 6 & 7 - PERIODIC REPORTING, BRIEFING, AND FINAL REPORT

Letter Progress Reports were submitted on June 11, August 11, and October 19 detailing the progress of the program to date. One Oral Review was held at Engineered Designs, Inc. in Cincinnati on July 14, 1992. A Final Briefing was held at Ft. Eustis on October, 19, 1992, and the Final Report is being submitted as this document. Video tape of the dynamic testing and the initial static testing was also provided to the Technical Contracting Officer.

CONCLUSIONS BASED ON PHASE I EFFORTS

The objectives of the Phase I effort have been met, but with mixed results. The manufacture of bush seal test articles for low temperature testing was demonstrated. The manufacturing methods used to generate the bristle bundles was successful. While the methods used were labor intensive, they were chosen to allow easy transition to an automated production process.

The epoxying of the bristle bundles into the seal housings was educational. Several problems were encountered such as bristle voids, bundle gaps, and epoxy control, but they were addressed as they were discovered. The lack of good bonding in the full ring bush seal appeared to be epoxy quantity related. It should be noted that the epoxy system of bundle attachment is not intended for production manufacturing. It was only used on the low temperature test articles because it allows them to be manufactured quickly at relatively low cost. The manufacturing method for high temperature bush seals will be further developed using braze and/or weld techniques to attach the bristle bundles.

The study of the potential performance enhancement of the bush seal relative to a conventional labyrinth seal showed that if the bush seal could be designed with a reduced initial gap and/or behaves as predicted by not degrading during rotor excursion rubs, the amount of air leakage can be reduced. Typical engine seal sizes and environments were investigated, but because no actual field experience was available to Engineered Designs, the performance enhancement could not be quantified. Best guess conditions were used to establish the potential enhancements.

The dynamic testing of the bush seal specimen provided very encouraging results. Three various bristle lay angle specimen were evaluated. It was concluded that the 45 degree lay angle was probably best. Because the bristles for this specimen are longer for the same radial height, they have increased flexibility. This results in less contact pressure during a rotor excursion, intuitively resulting in less heat generation and less potential for wear.

From the amount of wear measured on the specimen, it was concluded that the bristles do deflect and spread apart during a rotating labyrinth tooth excursion into the bush seal. Measured amounts of wear were between 0.001 and 0.0025 inches for all dynamic testing. This testing included simulated excursions to various depths for various periods of time. The amount of measured wear appears to be insensitive to both the depth and duration of the incursion under low temperature and low speed conditions. If this type of insensitivity holds true for the high temperature/high speed conditions, the bush seal concept will be able to be successfully applied to advanced gas turbine engines.

The static testing is the area which showed mixed results. The visual observation of the bristles' behavior during pressurized air flow showed that the bristles did not vibrate or have excessive deflections. The higher than predicted flow which was measured showed that the exposed axial face of the bristles should be minimized and that the method of bonding the bristle bundles must be positive.

During the Phase I effort, no obstacles were encountered which would indicate that the bush seal concept would not work for gas turbine engine applications. All objectives were accomplished with some very favorable results in the lack of a vibratory response in the bristles during pressurization and the bristle reaction to a rotating labyrinth tooth. Many lessons were also learned during the manufacturing development of the bush seal test articles. Most of the lessons can be applied to the further development of the high temperature/high speed bush seals to meet the aggressive program goals of 1450°F and 1450 feet per second tip speed.

APPENDIX A

STATIC TEST HEAD ASSEMBLY DRAWING - P893A001

The following pages contain the Static Test Head Assembly Drawing P/N P893A001 (Sheets 1 and 2) which was used during the static testing of the full ring bush seal test article.

QTY PER ASSY --	--	--	02	01	MATERIAL	PART NUMBER	NOMENCLATURE	ITEM NO
			1	1	AMS 4340	P893D026	RING, BACK-UP	25
			1	–	POLYCARB.	P893D025	PORT, COVER	24
			1	1	---------	P893G008	BUSH SEAL TEST ARTICLE	23
			16	16	STEEL	1/4-20UNCx1.00	SCREW, SOCKET HEAD CAP	22
			–	1	STEEL	S-400-P	PLUG (SWAGELOK)	21
			–	1	STEEL	S-400-1-4	FITTING (SWAGELOK)	20
			1	–	BRASS/AL	TS-4 (200psig)	BURST DISC ASSY (CDC)	19
			1	1	VITON	PARKER 3-912	PACKING, PREFORMED	18
			1	1	STEEL	S-1610-P	PLUG (SWAGELOK)	17
			1	1	STEEL	S-1610-1-12ST	FITTING (SWAGELOK)	16
			4	4	STEEL	S-100-P	PLUG (SWAGELOK)	15
			4	4	STEEL	S-100-1-1-BT	FITTING (SWAGELOK)	14
			8	8	STEEL	1/4-20UNCx1 00	SCREW, SOCKET HEAD CAP	13
			1	1	VITON	PARKER 2-164	PACKING, PREFORMED	12
			4	4	STEEL	5/16-18UNCx 875	SCREW, SOCKET HEAD CAP	11
			AR	AR	AMS 5510	AN960C516	WASHER, FLAT	10
			16	16	STEEL	1/4-20UNCx1 00	SCREW, SOCKET HEAD CAP	09
			ALT	ALT	AISI 1080	WH-625 (SMALLEY)	RING, RETAINING	08
			1	1	AISI 1080	RR-625 (RAMSEY)	RING, RETAINING	08
			2	2	AMS 5735	MS9390-170	PIN, DOWEL	07
			1	1	AMS 4340	P893D007	BASE, TEST HEAD	06
			1	1	AMS 4340	P893D005	SEAL, TOOTHED	05
			1	1	AMS 4340	P893D004	SUPPORT, SEAL	04
			–	1	AMS 4340	P893D003	PORT, COVER	03
			1	1	AMS 4340	P893G002	HOUSING ASSY	02
				–	--------	P893A001-02	ASSY, STATIC TEST HEAD	01
			–		--------	P893A001-01	ASSY, STATIC TEST HEAD	01

ENGINEERED DESIGNS, INC.
P.O. BOX 8125
WEST CHESTER, OHIO 45C69

CAGE CODE 0GP42	CONTRACT	DWG TYPE ASSEMBLY
DRAWN BY JL CABE	DWG TITLE STATIC TEST HEAD ASSEMBLY	
CHECKED BY JL CABE		
ENGINEERING JL CABE	DWG NUMBER P893A001	
ISSUED 05/15/92		
FILE 893A0011	SCALE NONE	SHEET 1 OF 4

EDF 10 (1/90)

FIGURE A-1. STATIC TEST HEAD ASSEMBLY DRAWING - P893A001 SH 1

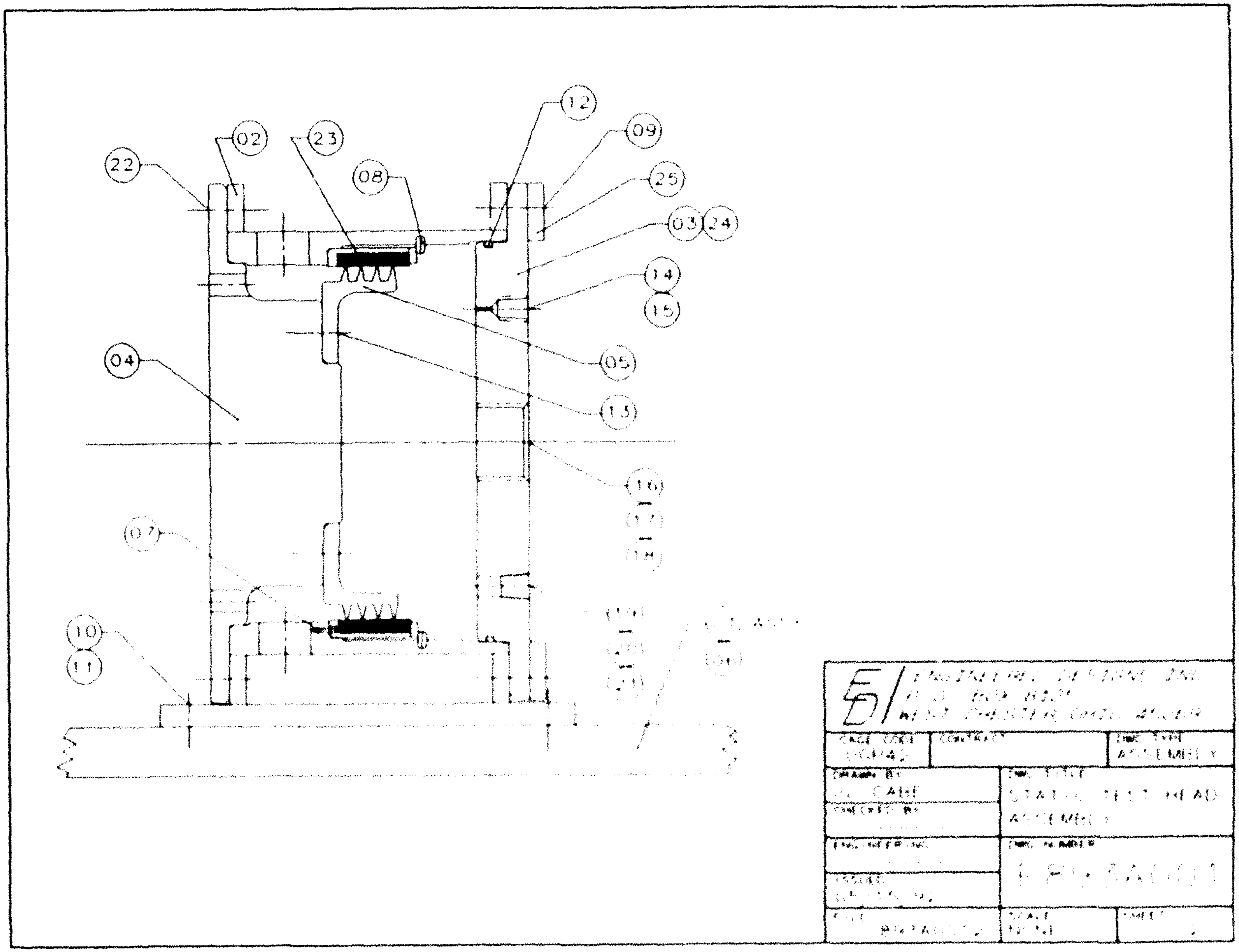

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FIGURE A-2. STATIC TEST HEAD ASSEMBLY DRAWING - P893A001 SH 2

APPENDIX B

VERMESE ORIFICE EQUATION

The following equation of isentropic flow was used during Phase I to predict the performance of conventional labyrinth and bush seals.

$$W = \frac{(0.79)\, C\, A\, P_o\, B}{\sqrt{T_o}\ \sqrt{1-a}}$$

Where: W = mass flow of air - lbm/sec

C = coefficient of flow

A = gap flow area - sq in

P_o = upstream pressure - psia

$$B = \sqrt{\frac{1-(P_n/P_o)^2}{n-[\log e\,(P_n/P_o)]}}$$

T_o = upstream air temperature - °R

a = kinet.. energv factor

$$a = \frac{8.52}{(P-L)/Cl + 7.23}$$

P_n = discharge static pressure - psia

n = number of labyrinth teeth

P = tooth pitch - inch

L = tooth tip width - inch

Cl = radial gap - inch

APPENDIX C

BUSH SEAL STATIC TEST DATA

Test data generated during the static testing of the full ring bush seal test article and the subsequent investigative test sequences are tabulated in the following tables. Each test sequence is labeled with a sequential letter, along with having all of the test points consecutively numbered. If required, raw data was corrected for ambient test conditions to a standard volumetric flow at $70^{o}F$ and 14.7 psia.

TABLE C-1. TEST SEQUENCE A DATA

A. BUSH SEAL STATIC TEST-METAL COVER (10/11/92)

DATA POINT	SEAL HSG XDUCER (psig)	PRESSURE GAUGE (psig)	REGULATOR XDUCER (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
01	10	25	25.9	82	80	0	0	1.011	79.109	0.099
02	10	25	25.9	82	80	0	0	1.011	79.109	0.099
03	15	33.5	33.9	81.3	92	1	0	1.011	92.024	0.115
04	10	25	25.8	81.2	80	0	0	1.011	79.168	0.099
05	20	40	41.5	82.9	103	2	0	1.012	103.745	0.130
06	10	24.9	25.7	83	80	0	0	1.012	79.037	0.099
07	30	54	56	86.3	130	6.6	0	1.015	134.547	0.168
08	10	24.9	25.6	86.9	80	0	0	1.016	78.754	0.098
09	40	67.5	70.1	92.4	163	6	0	1.021	165.538	0.207
10	10	24.9	25.5	90.9	80	0	0	1.020	78.468	0.098
11	50	80	83.2	97.5	190	6	0	1.026	191.105	0.239
12	10	24.9	25.5	96	80	0	0	1.024	78.107	0.098
13	52.3	83.8	86.7	100.9	195	6	0	1.029	195.385	0.244
14	10	24.9	25.4	99.1	80	0	0	1.027	77.890	0.097

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-2. TEST SEQUENCE B DATA

B. BUSH SEAL STATIC TEST-POLYCARBONATE COVER (10/11/92)

DATA POINT	SEAL HSG XDUCER (psig)	PRESSURE GAUGE (psig)	REGULATOR XDUCER (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
15	10	25	25.5	71.4	78	0	0	1.001	77.897	0.097
16	15	33	33.5	71.1	90	1	0	1.001	90.906	0.114
17	10	25	25.2	71.5	78	0	0	1.001	77.890	0.097
18	20	40	40.8	74	102	2	0	1.004	103.610	0.130
19	10	25	25.5	74.7	79	0	0	1.004	78.652	0.098
20	30	54	55.4	79.6	130	6.6	0	1.009	135.379	0.169
21	10	25	25.3	80.4	79	0	0	1.010	78.236	0.098
22	40	67	70.1	92.4	161	6	0	1.021	163.579	0.204
23	10	25	25.3	90.8	79	0	0	1.019	[illegible].494	0.097
24	50	81	83.9	96.1	190	6	0	1.024	191.345	0.239
25	10	STABLE RDG NOT OBTAINED - CONDENSATION					0	0.932	0.000	0.000
26	52.3	83.8	86.3	96.9	195	6	0	1.025	196.085	0.245
27	10	25	25.6	98	80	0	0	1.026	77.967	0.097

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-3. TEST SEQUENCE C DATA

C. INVESTIGATION TEST WITH FLOWMETER UPSTREAM OF REGULATOR - 1/4" ORIFICE (11/21/92)

DATA POINT	SEAL HSG XDUCER (psig)	PRESSURE GAUGE (psig)	REGULATOR XDUCER (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
28		115	10	65.3	20	-6	0	0.996	14.062	0.018
29		113.5	20	65.3	30	-5	0	0.996	25.112	0.031
30		112	30	65.3	40	-3	0	0.996	37.165	0.046
31		110	40	65.1	48	-3	0	0.995	45.209	0.057
32		109	50	64.9	55	-3	0	0.995	52.252	0.065
33		107	60	64.9	65	-2	0	0.995	63.305	0.079
34		106	70	65.2	70	-1	0	0.995	69.315	0.087
35		105	80	65.7	80	0	0	0.996	80.327	0.100
36		104	90	66.8	90	1	0	0.997	91.276	0.114

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-4. TEST SEQUENCE D DATA

D. INVESTIGATION TEST WITH FLOWMETER DOWNSTREAM OF REGULATOR - 1/4" ORIFICE (11/21/92)

DATA POINT	PRESSURE GAUGE (psig)	F/M DELTA P (psia)	P1 (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
37	10	-3	7	69.2	30	-5	2.155	0.999	13.932	0.017
38	20	-4	16	69	45	-3	1.818	0.999	24.775	0.031
39	30	-4	26	68.7	54	-3	1.602	0.999	33.752	0.042
40	40	-5	35	68.8	60	-2	1.448	0.999	41.482	0.052
41	50	-6	44	69	66	-2	1.331	0.999	49.616	0.062
42	60	-7	53	69	70	-1	1.239	0.999	56.544	0.071
43	70	-8	62	68.7	75	-1	1.164	0.999	64.529	0.081
44	80	-10	70	68.5	80	0	1.101	0.999	72.795	0.091
45	90	-10	80	68.7	84	0	1.047	0.999	80.353	0.100
46	100	-12	88	69.7	90	1	1.000	1.000	90.025	0.113

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-5. TEST SEQUENCE E DATA

E. INVESTIGATION TEST WITH FLOWMETER DOWNSTREAM OF REGULATOR - 1/4" SHARP ORIFICE (11/21/92)

DATA POINT	PRESSURE GAUGE (psig)	F/M DELTA P (psia)	P1 (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
47	10	-3	7	69.2	30	-5	2.155	0.999	13.932	0.017
48	20	-4	16	69	45	-3	1.818	0.999	24.775	0.031
49	30	-4	26	68.7	54	-3	1.602	0.999	33.752	0.042
50	40	-5	35	68.8	60	-2	1.448	0.999	41.482	0.052
51	50	-6	44	69	70	-1	1.331	0.999	52.623	0.066
52	60	-7	53	69	70	-1	1.239	0.999	56.544	0.071
53	70	-8	62	68.7	75	-1	1.164	0.999	64.529	0.081
54	80	-10	70	68.5	80	0	1.101	0.999	72.795	0.091
55	90	-10	80	68.7	85	0	1.047	0.999	81.310	0.102
56	100	-12	88	69.7	90	1	1.000	1.000	90.025	0.113

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-6. TEST SEQUENCE F DATA

F. INVESTIGATION TEST WITH MACHINED RING (11/21/92)

DATA POINT	SEAL HSG XDUCER (psig)	PRESSURE GAUGE (psig)	REGULATOR XDUCER (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
57	10	14	14	67.5	25	-6	1.999	0.998	9.527	0.012
58	20	24.5	24.8	67.4	35	-4	1.711	0.998	18.167	0.023
59	30	35	35.2	67.2	37.5	-3	1.519	0.997	22.770	0.028
60	40	45	45.5	66.8	42.5	-3	1.386	0.997	28.584	0.036
61	50	55	55.7	66.6	46	-3	1.283	0.997	33.628	0.042
62	60	65	65.8	66.6	50	-3	1.200	0.997	39.305	0.049
63	70	76	75.9	66.8	54	-2	1.125	0.997	46.381	0.058
64	80	86	86.4	68.1	56	-2	1.067	0.998	50.688	0.063
65	90	96	96.6	70.4	59	-2	1.018	1.000	55.976	0.070
66	100	106	107.2	72.8	60	-2	0.975	1.003	59.341	0.074

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-7. TEST SEQUENCE G DATA

G. STATIC BUSH SEAL TEST (11/21/92)

DATA POINT	SEAL HSG XDUCER (psig)	PRESSURE GAUGE (psig)	REGULATOR XDUCER (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
67	10	24	24.7	66.4	110	1	1.722	0.997	64.696	0.081
68	20	39	40.2	67	142	7	1.461	0.997	102.241	0.128
69	30	53	54.8	82	165	6	1.302	1.011	129.911	0.162
70	40	66	68.6	99.1	185	6	1.192	1.027	155.985	0.195
71	50	75	77.8	113.4	200	6	1.131	1.040	175.142	0.219

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-8. TEST SEQUENCE H DATA

H. STATIC BUSH SEAL TEST WITH .003" RADIAL SHIM INSTALLED (11/21/92)

DATA POINT	SEAL HSG XDUCER (psig)	PRESSURE GAUGE (psig)	REGULATOR XDUCER (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
72	10	22	23.3	87.9	100	1	1.768	1.017	56.190	0.070
73	20	37	37.9	84.3	130	6	1.489	1.013	90.099	0.113
74	30	50	51.4	84.1	152	7	1.331	1.013	117.860	0.147
75	40	63	65.3	88.7	170	6	1.215	1.017	142.368	0.178
76	50	76	78.1	99.8	187	6	1.125	1.028	166.994	0.209

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-9. TEST SEQUENCE I DATA

I. STATIC BUSH SEAL TEST WITH .003" RADIAL SHIM INSTALLED PLUS BRISTLE FACE SEALED (11/22/92)

DATA POINT	SEAL HSG XDUCER (psig)	PRESSURE GAUGE (psig)	REGULATOR XDUCER (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
77	10	12.5	12	67.3	<20	0	2.054	0.997	0.000	0.000
78	20	22.5	22.9	67	<20	0	1.756	0.997	0.000	0.000
79	30	34	34.1	66.8	28	-5	1.535	0.997	15.032	0.019
80	40	45	45.2	66.4	40	-3	1.386	0.997	26.785	0.033
81	50	55.5	56	65.2	49	-3	1.278	0.995	36.151	0.045
82	60	66	67	64.4	59	-2	1.192	0.995	48.066	0.060
83	70	77	78	64.5	68	-2	1.118	0.995	59.321	0.074
84	80	88	89.2	66.1	77	-1	1.057	0.996	72.181	0.090
85	90	99	100.5	70.9	90	-1	1.004	1.001	88.536	0.111

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

TABLE C-10. TEST SEQUENCE J DATA

J. STATIC BUSH SEAL TEST WITH BRISTLE FACE SEALED (11/22/92)

DATA POINT	SEAL HSG XDUCER (psig)	PRESSURE GAUGE (psig)	REGULATOR XDUCER (psig)	REGULATOR T/C (F)	FLOWMETER Indicated (cfm)	FLOWMETER CORRECTIONS CAL ERROR	f1 PRESS	f2 TEMP	CORRECTED FLOW (scfm)*	MASS FLOW lbm/sec
86	10	21	21.2	72.4	85	0	1.792	1.002	47.314	0.059
87	20	33.5	34.3	70.2	108	1	1.543	1.000	70.646	0.088
88	30	45.5	46.7	68.7	124	6	1.380	0.999	94.296	0.118
89	40	56.5	58.1	71.4	135	6	1.269	1.001	110.944	0.139
90	50	67	69.5	76.4	143	7	1.185	1.006	125.839	0.157
91	60	77	78.9	87.1	145	7	1.118	1.016	133.768	0.167
92	70	86	88.5	99.2	137	6	1.067	1.027	130.444	0.163
93	80	93	94.6	103.7	121	6	1.032	1.031	119.328	0.149
94	84.5	96.5	98.4	107	117	6	1.016	1.034	117.091	0.146

* STANDARD CUBIC FOOT PER MINUTE = FLOW(cfm) OF AIR @ 70F/14.7psia

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